

**\*\*Volume Title\*\***

*ASP Conference Series, Vol. \*\*Volume Number\*\**

**\*\*Author\*\***

© **\*\*Copyright Year\*\*** *Astronomical Society of the Pacific*

## Excitation of stellar pulsations

Günter Houdek

*Institute of Astronomy, University of Vienna, 1180 Vienna, Austria*

**Abstract.** In this review I present an overview of our current understanding of the physical mechanisms that are responsible for the excitation of pulsations in stars with surface convection zones. These are typically cooler stars such as the Delta Scuti stars, and stars supporting solar-like oscillations.

### 1. Introduction

Convection dynamics affects the driving and damping of pulsations particularly in stars with convectively unstable outer layers, including also the F stars which have rather shallow surface convection zones and in which solar-like oscillations have been observed. The type of stars in which the coupling between pulsation and the turbulent velocity field is important are, for example, the rapidly oscillating Ap stars, Delta Scuti stars,  $\gamma$  Doradus, RR Lyrae stars, and stars which support stochastically excited oscillations. In this review I shall only address two of them, Delta Scuti stars and solar-type stars.

### 2. Delta Scuti stars

Delta Scuti ( $\delta$  Sct) stars have masses  $M$  between  $1.5 \lesssim M / M_{\odot} \lesssim 2.5$  and luminosities  $L$  between  $0.6 \lesssim \log L / L_{\odot} \lesssim 2.0$ . They are in the central or shell hydrogen burning phase with complex multiperiodic oscillation spectra, including both radial and nonradial modes (e.g., 79 pulsation modes have been detected in FG Vir, Breger et al. 2005). The oscillations are low-order p modes with relatively small amplitudes ranging from  $10^{-3} - 0.1$  mmag and with periods between 18 min and 8 h. The modes are driven by the kappa mechanism in the second stage of helium ionization. Cooler  $\delta$  Sct stars have substantial surface convection zones and, similarly to solar-like stars, the stability properties of the oscillation modes are crucially affected by the convection dynamics. In particular, the return to stability of low-order p modes at the cool boundary of the classical instability strip is predicted only with the inclusion of convection dynamics in the stability analysis (e.g., Houdek et al. 1999, Houdek 2000, Xiong & Deng 2001, Dupret et al. 2005). These authors use different implementations for modelling the interaction of the turbulent velocity field with the pulsation. The currently most commonly used time-dependent convection formulations for studying the stability of stellar pulsations are those by Gough (1965, 1977a,b), Xiong (1977, 1989) and Grigahcène et al. (2005) the latter being a generalization of Unno's (1967) formulation. Although they all adopt the Boussinesq approximation to the fluid equations they differ substantially in detail.

A brief discussion of the main differences between these convection models was recently given by Houdek (2008). All three convection formulations model successfully the location of the red edge of the classical instability strip (IS), however, the physical mechanism responsible for the return to stability is very different in all three computations. Dupret et al. (2005) report that it is predominantly the convective heat flux, Xiong & Deng (2001) the viscosity of the small-scale turbulence, and Houdek (2000) that it is predominantly the momentum flux (turbulent pressure  $p_t$ ) that stabilizes the pulsation modes at the red edge of the IS. The results of these stability calculations are illustrated in Figure 1 in terms of accumulated work integrals  $W$  for stellar models located just outside the cool edge of the IS, i.e. for models for which the pulsation is found to be stable.

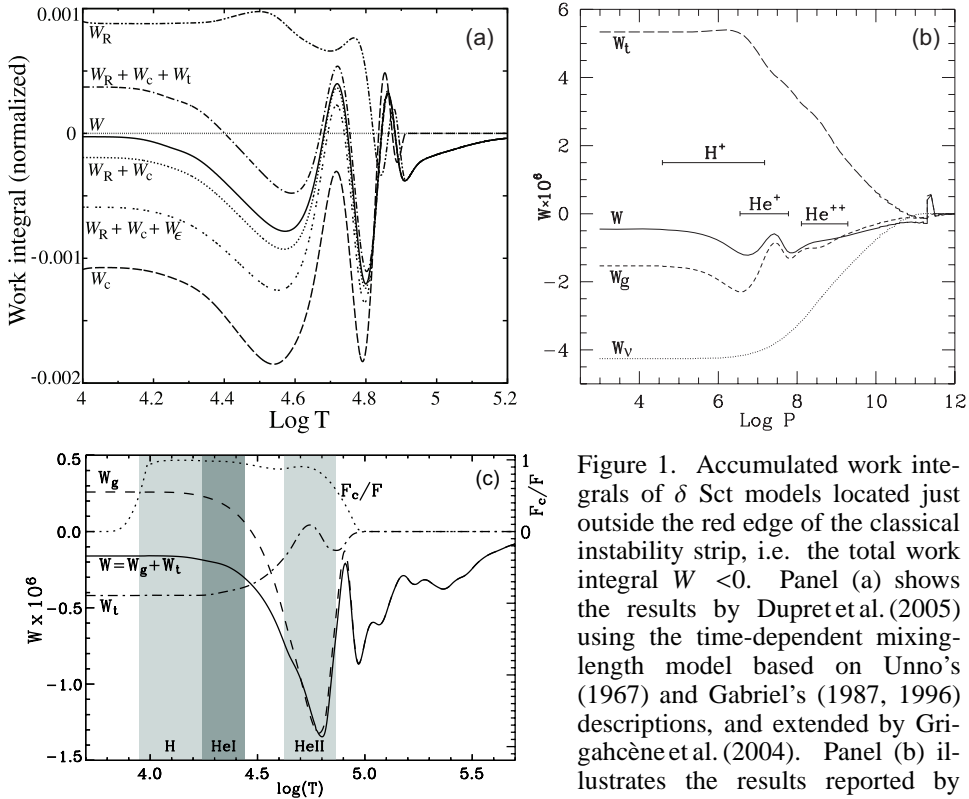


Figure 1. Accumulated work integrals of  $\delta$  Sct models located just outside the red edge of the classical instability strip, i.e. the total work integral  $W < 0$ . Panel (a) shows the results by Dupret et al. (2005) using the time-dependent mixing-length model based on Unno's (1967) and Gabriel's (1987, 1996) descriptions, and extended by Grigahcène et al. (2004). Panel (b) illustrates the results reported by Xiong & Deng (2007) using Xiong's

(1989) Reynolds-stress-model-like time-dependent convection formulation. Panel (c) are the results by Houdek (2000) using Gough's (1977a,b) nonlocal, time-dependent mixing-length model. Panel (a) is adapted from Dupret et al. (2005), panel (b) from Xiong & Deng (2007), and (c) from Houdek (2000).

Nonadiabatic pulsation computations provide complex eigenfunctions and eigenfrequencies  $\omega = \omega_r + i\omega_i$  for modes with angular frequencies  $\omega_r$  and growth/damping rates  $\omega_i$ . Work integrals  $W$  for complex eigenfrequencies were, for example, provided by Baker & Gough (1979) and can be divided into contributions arising from terms associated with thermal energy equation (e.g., gas pressure perturbation,  $W_g$ ), and terms associated with the momentum equation (e.g., momentum flux perturbation,  $W_t$ ).

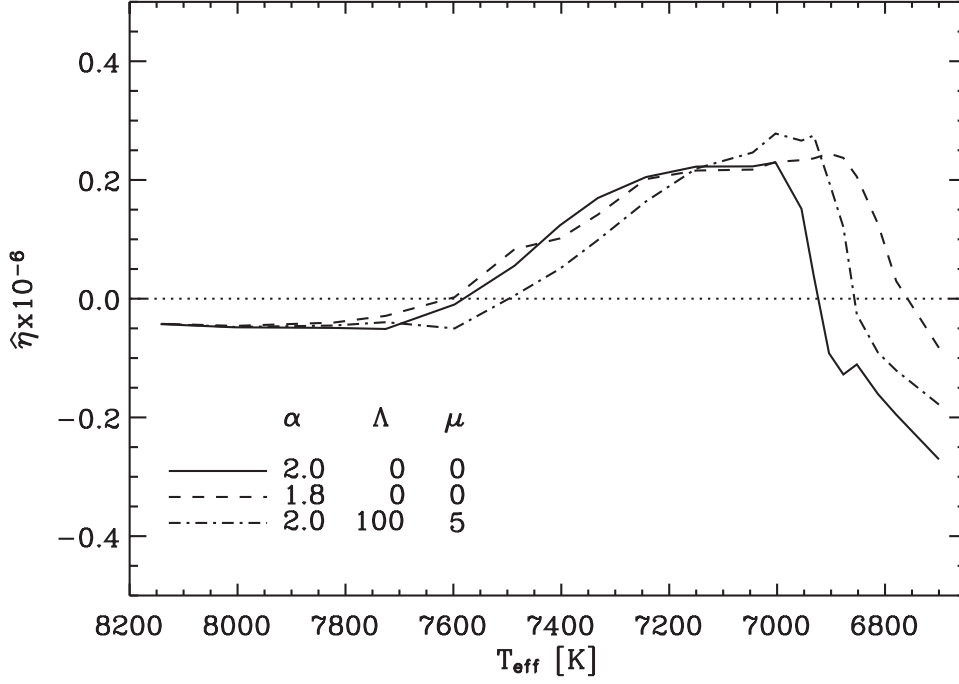


Figure 2. Linear stability coefficients  $\hat{\eta} := \omega_i/\omega_r$  (positive values indicate instability) of the fundamental radial acoustic mode for an  $1.7 M_{\odot}$   $\delta$  Sct star in the hydrogen-burning phase crossing the instability strip. Results are shown for two different mixing-length parameters and for a calculation in which the effect of acoustic radiation in the equilibrium model was included according to expression (1).

The upper left panel (a) of Figure 1 shows the results of Dupret et al. (2005). The individual contributions to the total  $W$  arising from the radiative flux,  $W_R$ , the convective flux,  $W_c$ , the turbulent pressure,  $W_t$  ( $W_R + W_c + W_t$ ), and from the perturbation of the turbulent kinetic energy dissipation,  $W_\epsilon$  ( $W_R + W_c + W_\epsilon$ ) are indicated by different line styles. It demonstrates the near cancellation effect between the contributions of the turbulent kinetic energy dissipation,  $W_\epsilon$ , and turbulent pressure,  $W_t$ , making the contribution from the fluctuating convective heat flux,  $W_c$ , the dominating damping term.

The results of the calculations by Xiong & Deng (2001) are displayed in the upper right panel (b) of Figure 1. Contributions to the total  $W = W_g + W_t + W_v$  arising from the gas pressure fluctuations,  $W_g$ , the turbulent pressure fluctuations,  $W_t$ , and from an effective viscosity from the small-scale turbulence,  $W_v$ , are indicated by different line styles. The ionization zones of hydrogen (H) and helium (He) are indicated. In this calculation the dominating agent for making the pulsations stable is the damping contribution from the small-scale turbulence,  $W_v$ .

Panel (c) of Figure 1 shows the results of Houdek (2000) using Gough's (1977a,b) convection formulation. Contributions to  $W = W_g + W_t$  (solid curve) arising from the gas pressure perturbation,  $W_g$  (dashed curve), and the turbulent pressure fluctuations,  $W_t$  (dot-dashed curve), are indicated. The dotted curve is the ratio of the convective to the total heat flux,  $F_c/F$ , and the ionization zones of H and He (5% to 95%) are indicated. In this calculation it is the contribution from the turbulent pressure fluctuation,  $W_t$ , that stabilizes the pulsation mode.

It is interesting to note that all three convection descriptions include, although in different ways, the perturbations of the turbulent fluxes, but Gough (1977a), Xiong (1977, 1989) and Unno et al. (1989) did not include the contribution  $W_\epsilon$  to the work integral because in the Boussinesq approximation (Spiegel & Veronis 1960) the viscous dissipation is neglected in the thermal energy equation. In practise, however, this term may be important.

All three convection models need calibration for the mixing-length parameter  $\alpha$ . The effect of varying  $\alpha$  on the location of the IS for the fundamental radial acoustic mode is illustrated in Figure 2 for an  $1.7 M_\odot$  star in the central hydrogen-burning phase. Decreasing  $\alpha$  results in a significant shift of the cool boundary of the IS towards lower surface temperatures, whereas the blue edge is essentially unaffected. This comes about because reducing  $\alpha$  diminishes the stabilizing effect of the turbulence on the pulsations, which is, however, offset by the increasing efficacy of the surface convection with decreasing surface temperature  $T_{\text{eff}}$  of the star. The observed location of the cool edge of the IS can therefore be used to calibrate  $\alpha$  in  $\delta$  Sct stars.

Another effect, yet neglected in essentially all stability computations, is the effect of acoustic radiation in the equilibrium model. The generation of acoustic waves is omitted in convection models which assume either the anelastic (Gough 1969) or Boussinesq approximation (Spiegel & Veronis 1960) to the fluid equations. However, through the generation of sound waves, kinetic energy from the turbulent motion will be converted into acoustic radiation (Lighthill 1952) and thus reduce the efficacy with which the motion might otherwise have released potential energy originating from the buoyancy forces. This effect may become important in stars with large turbulent Mach numbers  $M_t := w/c$ , where  $w$  is the vertical rms component of the convective velocity field  $\mathbf{u} = (u, v, w)$ , and  $c$  is sound speed. In the phenomenological picture of an overturning convective fluid element (eddy), which maintains balance between buoyancy forces and turbulent drag by continuous exchange of momentum with other elements and its surrounding (e.g., Unno 1967), the equation of motion for the turbulent element of vertical size  $\ell$  can be written as

$$\frac{2w^2}{\ell^2} = g\widehat{\alpha}T' - \frac{P_{\text{ac}}}{\rho w}, \quad (1)$$

where  $T'$  is the Eulerian temperature fluctuation,  $\widehat{\alpha}$  the coefficient of thermal expansion, and  $g$  is the acceleration due to gravity. The rate of energy of acoustic radiation per unit volume,  $P_{\text{ac}}$  is estimated according to the Lighthill-Proudman formula

$$P_{\text{ac}} = \Lambda \frac{\rho w^3}{\ell} \left( \frac{w}{c} \right)^\mu, \quad (2)$$

where  $\Lambda$  and  $\mu$  are the coefficients for emissivity and Mach-number dependence. If the emission of acoustic waves by homogeneous, isotropic turbulence is dominated by the largest convective eddies, the acoustic emission  $P_{\text{ac}}$  scales with a Mach-number dependence  $\mu = 5$  (Lighthill 1952) and the emissivity coefficient  $\Lambda \simeq 100$  for a solar model (Stein 1968), which we also adopt here in our estimate for  $P_{\text{ac}}$ .

The effect of the acoustic radiation  $P_{\text{ac}}$  in the mean model on the location of the instability strip for the fundamental radial acoustic mode is illustrated by the dot-dashed curve in Figure 2 for an  $1.7 M_\odot$  star in the central hydrogen-burning phase. At the cool edge the effect of including  $P_{\text{ac}}$  is similar to reducing the mixing length, however, at the hot (blue) edge of the IS  $P_{\text{ac}}$  has a much larger effect than changing the vertical extent of the convective elements.

### 3. Solar-like stars

Kepler has been providing data of solar-like oscillations with unprecedented quality in more than 2000 stars (e.g., Chaplin et al. 2011; García et al. 2011; Huber et al. 2011b). One of the many important outcomes of the Kepler data analyses is the confirmation of the problem of reproducing theoretically the observed amplitudes of stochastically excited modes in stars hotter than the Sun. In general, Kepler observed photometric amplitudes in stars located near the red edge of the IS that are rather similar to those found in the Sun, whereas theoretical amplitude estimates are up to 3-4 times larger than the Kepler values. This discrepancy in the oscillation amplitudes was already recognised before (Houdek 2006) when first ground-based spectroscopic observations were available, such as for the F-star Procyon (e.g. Martić et al. 1999, Arentoft et al. 2008). It therefore behoves us to address the possible reasons why our current theory fails to reproduce observed amplitudes of solar-like oscillations in hotter stars. Reviews on the theory and modelling of stochastically excited modes were recently given, for example, by Appourchaux et al. (2009) and Houdek (2010). Therefore I shall summarize only the most important matters for our discussion.

Solar-like oscillations are intrinsically damped but driven stochastically by the vigorous turbulent convection in the very outer stellar layers. The height  $H$  of a single peak in the observed oscillation power spectrum can be obtained from taking the Fourier transformation of a damped, harmonic oscillator for the surface displacement followed by an integration over frequency to obtain the total mean energy  $E$  in a single pulsation mode with (normalized) inertia  $I$  (e.g. Chaplin et al. 2005; Houdek 2006). Provided that the observing time is long compared to the mode lifetime the height  $H$  in units of  $\text{cm}^2 \text{s}^{-2} \text{Hz}^{-1}$  is given by

$$H = \frac{2E}{\eta I} = \frac{P}{\eta^2 I}, \quad (3)$$

where  $\eta$  is the damping rate or inverse of the mode lifetime, and  $P$  is the energy-supply rate in  $\text{erg s}^{-1}$ . If only the Reynolds stress driving term is considered in the equations of motions, the energy-supply rate  $P$  for radial models is given by (e.g. Chaplin et al. 2005)

$$P = \frac{\pi}{9I} \int_0^R \ell^3 \left( \Phi \Psi r p_t \frac{\partial \xi_r}{\partial r} \right)^2 \mathcal{S}(\omega_r; r) dr, \quad (4)$$

with

$$\mathcal{S}(\omega_r; r) = \int_0^\infty \kappa^{-2} \tilde{E}^2(\kappa) \tilde{\Omega}(\tau_k; \omega_r) d\kappa, \quad (5)$$

where  $R$  is surface radius,  $p_t = \langle \rho w w \rangle$  is the  $(r, r)$  component of the (mean) Reynolds stress tensor (also known as turbulent pressure; angular brackets denote an ensemble average),  $\xi_r$  is the normalized radial part of the pulsation eigenfunction  $\xi$ , and the product of  $\Phi$  and  $\Psi$  is a factor of unity accounting for the anisotropy of the turbulent velocity field  $\mathbf{u}$ . The spectral function  $\mathcal{S}$  accounts for contributions to  $P$  from the small-scale turbulence and includes the normalized spatial turbulent energy spectrum  $\tilde{E}(k)$  and the frequency-dependent factor  $\tilde{\Omega}(\tau_k; \omega_r)$ ;  $\tau_k := \lambda / k u_k$  is the correlation time scale of eddies with wave number  $k$  and velocity  $u_k$  ( $\lambda$  is a factor of order unity and accounts for uncertainties in defining  $\tau_k$ ), and  $\kappa = k\ell/\pi$ . For  $\tilde{E}(k)$  it has been common to adopt, for example, the Kolmogorov (Kolmogorov 1941) spectrum. For the frequency-dependent factor  $\Omega(\tau_k; \omega)$ , however, which is used for evaluating the self-convolution

$\tilde{\Omega}(\omega_r, \tau_k; r) = \int \Omega(\omega, \tau_k; r) \Omega(\omega_r - \omega, \tau_k; r) d\omega$  in equation (5), no satisfactory theory exists. The two commonly adopted forms are

– the Gaussian factor (Stein 1967),

$$\Omega_G(\omega; \tau_k) = \frac{\tau_k}{\sqrt{2\pi}} e^{-(\omega\tau_k/\sqrt{2})^2}; \quad (6)$$

– the Lorentzian factor (Gough 1977b; Samadi et al. 2003; Chaplin et al. 2005),

$$\Omega_L(\omega; \tau_k) = \frac{\tau_k}{\pi \sqrt{2 \ln 2}} \frac{1}{1 + (\omega\tau_k/\sqrt{2 \ln 2})^2}. \quad (7)$$

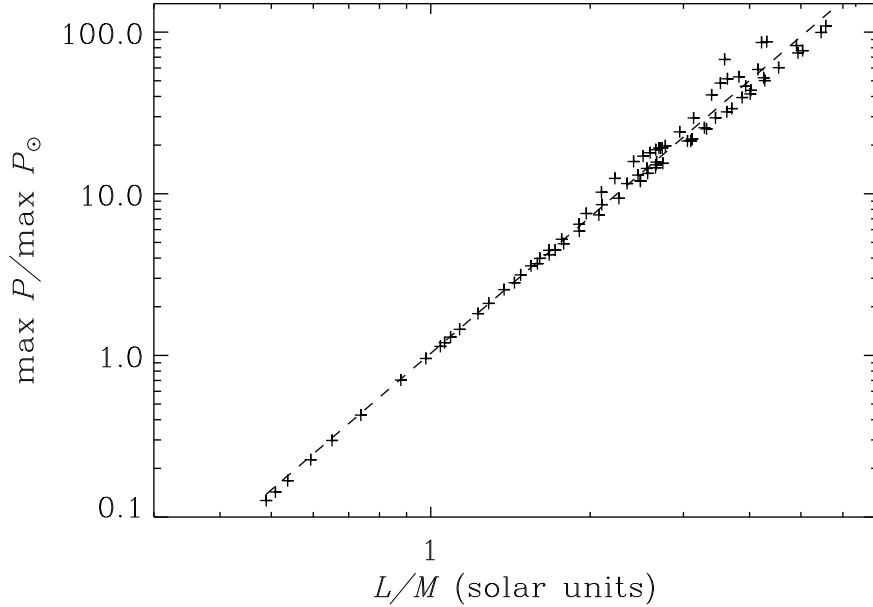


Figure 3. Maximum energy-supply rates  $P$  (equation 4) of stochastically excited oscillations in 83 (symbols) solar-like stellar models, computed in the manner of Chaplin et al. (2005) using a Gaussian frequency factor (equation 6). The dashed line is a fit to the 83 model data by linear least squares, leading to an exponent  $s = 2.80$  in the scaling relation  $\max(P)/\max(P_\odot) \sim (L/M)^s$ , where  $L$  and  $M$  are in solar units (see also Table 1).

The Lorentzian frequency factor is a result predicted for the largest, most-energetic eddies by the time-dependent mixing-length formulation of Gough (1977b), which decays more slowly with depth  $z$  and frequency  $\omega$  than the Gaussian factor. Consequently a substantial fraction to the integrand of equation (4) arises from eddies situated in the deeper layers of the Sun, resulting in a larger acoustic excitation rate  $P$ . Samadi et al. (2003) reported that Stein & Nordlund’s hydrodynamical simulations also suggest a Lorentzian frequency factor. However, Chaplin et al. (2005) reported that the Lorentzian time-correlation function leads to overestimated heights  $H$  at low frequencies for solar p modes. Recently, Belkacem et al. (2010) suggested to use a modified

Table 1. Comparison of different stochastic excitation calculations. The correlation parameter  $\lambda$  accounts for uncertainties in defining the correlation time scale of the turbulent eddies. The value of  $s$  is obtained from fitting  $(L/M)^s$  (in solar units) to the computed values of  $\max(P)/\max(P_\odot)$  of 83 solar-like stellar models by linear least squares (see Figure 3).

Excitation model	frequency factor $\Omega$	$\lambda$	$s$
Chaplin et al. (2005)	Gaussian (Stein 1967)	1.0	2.80
Samadi et al. (2003)	mod. Lorentzian (Belkacem et al. 2010)	1.5	2.87
Samadi et al. (2003)	mod. Lorentzian (Belkacem et al. 2010)	1.0	2.72

Lorentzian frequency factor, by cutting off the high-frequency tail, i.e. setting it to zero, for frequencies  $\omega > \omega_E$ . The cutoff frequency  $\omega_E$  is associated with the inverse of the Eulerian microscale (Tennekes & Lumley 1972) and can be estimated with the help of Kaneda’s (1993) ‘random sweeping model approximation’.

One of the many ongoing projects of the KASC (Kepler Asteroseismic Science Consortium) working group 1 “Solar-like p-mode oscillators” is the comparison of various stochastic excitation models. In a preliminary exercise a grid of 83 solar-type main-sequence models was computed in the manner of Chaplin et al. (2005) from which energy-supply rates  $P$  were computed with the excitation models by Samadi et al. (2001, 2003), using a Lorentzian frequency factor modified in the manner of Belkacem et al. (2010), and the excitation model by Chaplin et al. (2005) using a Gaussian frequency factor. All three computations assumed the same equilibrium models, pulsation eigenfunctions and mode inertia. The maximum values of the energy-supply rate  $P$  for the 83 solar-like stars with masses between  $0.9 \leq M / M_\odot \leq 1.5$ , evaluated with the excitation model of Chaplin et al. (2005, see equation 4), are plotted in Figure 3 as a function of  $L/M$ , where  $L$  and  $M$  are in solar units. The maximum values of  $P$  scale with  $(L/M)^s$ , where  $s = 2.80$ . The values for the exponent  $s$  for three different excitation model calculations, all using the same equilibrium model and pulsation eigenfunctions  $\xi$ , are listed in Table 1. It is interesting to note that the value of  $s$  varies only marginally between the different excitation models considered here, suggesting that the main problem of modelling the observed oscillation heights  $H$  (see expressions 3–5) in hotter main-sequence stars is very likely related to a failure in modelling either the equilibrium structure (e.g. the convective velocity field and consequently  $p_t$ ), the pulsation eigenfunctions  $\xi$ , or the mode damping rates  $\eta = -\omega_i$ .

### 3.1. Pulsation eigenfunctions

A very promising test of the pulsation theory, and in particular of the pulsation eigenfunctions, independent of an excitation model, is provided by comparing estimated intensity-velocity amplitude ratios,  $\Delta L / \Delta V_s$ , with observations (e.g. Houdek et al. 1995, 1999; Jimenez et al. 1999; Jimenez 2002; Houdek 2009). The estimated amplitude ratios are obtained from taking the ratios of the complex pulsation eigenfunctions provided by the nonadiabatic stability computations, which must include the coupling of the turbulent velocity field with the oscillations. A comparison of solar observations (Schrijver et al. 1991) with model predictions are displayed in the left panel of Figure 4, where the model results are depicted for velocity amplitudes computed at different at-

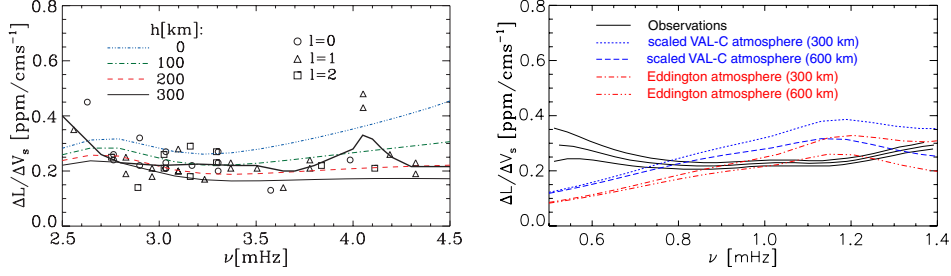


Figure 4. Comparison of computed amplitude ratios of stochastically excited modes with observations. Left: results are shown for a solar model at different atmospheric heights (curves) and for the Sun (symbols). The thick solid curve is a running mean average of the observed solar data (adapted from Houdek et al. 1999). Right: results are shown for a model of Procyon A at different atmospheric heights ( $h=300, 600$  km) and for two different atmospheres: a scaled VAL-C (Vernazza et al. 1981) and an Eddington atmosphere. The solid curves (thin curves indicate  $1\sigma$  uncertainties) are the observations (Huber et al. 2011a).

mospheric heights  $h$ . The square root of the mode kinetic energy per unit increment of radius  $r$ , which is proportional to  $r\rho^{1/2}\xi$ , increases rather slowly with height; the density  $\rho$ , however, decreases very rapidly and consequently the displacement eigenfunction  $\xi$  increases and the amplitude ratio decreases with height  $h$ .

In the right panel of Figure 4 model results for the F5 star Procyon A are compared with observations (Guenther et al. 2008) from the MOST spacecraft and contemporaneous radial velocity measurements by Arentoft et al. (2008). Theoretical results are shown for two stellar atmospheres at two different atmospheric heights. For both stellar atmospheres the agreement with the observations is less satisfactory than in the solar case, indicating that we do not represent correctly the shape of the pulsation eigenfunctions in the outer stellar layers. Moreover, the modelled amplitude ratios significantly depend on the adopted atmospheric model. Consequently there is need for adopting more realistically computed atmospheres in the equilibrium models, particularly for stars with much higher surface temperatures than the Sun.

Additionally to the effect of the atmospheric structure, the nonadiabatic eigenfunctions are also crucially modified by the dynamics of the turbulent velocity field in the convectively unstable surface layers. In particular the poorly modelled anisotropy of the turbulent velocity field  $\mathbf{u} = (u, v, w)$  in the near-surface layers crucially affects the magnitude and frequency-dependence of the amplitude ratios (Houdek 2011). In our current time-dependent convection model (Gough 1977a,b) the anisotropy  $\Phi := \mathbf{u} \cdot \mathbf{u} / w^2$  is parametrized by a constant value of order unity. Numerical simulations, however, indicate that  $\Phi$  varies rapidly with height in the outer stellar layers, as illustrated in Figure 5 for models of the Sun (left panel) and Procyon A (right panel). It therefore behoves us, with the help of numerical simulations, to develop a model for the velocity anisotropy  $\Phi$  for a more realistic description of the shapes of the convective cells as a function of stellar radius and consequently its effect on the pulsation eigenfunctions and frequencies.



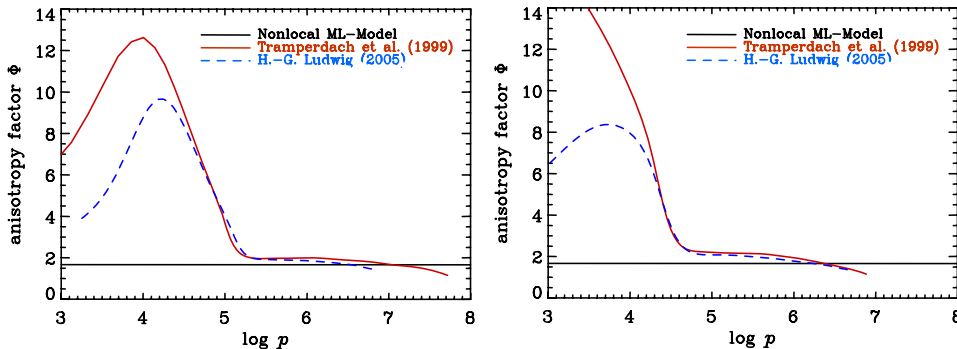


Figure 5. Anisotropy  $\Phi$  of the turbulent velocity field as a function of the depth variable pressure ( $p$ ) in the convectively unstable surface layers for models of the Sun (left panel) and Procyon A (right panel). Results are displayed for two different numerical simulations (red solid curve: R. Trampedach 1999, personal communication; blue dashed curve: H.-G. Ludwig 2005, personal communication) and for our current version of a semi-analytical convection model of Gough (1977a,b; black horizontal line). Figure adopted from Houdek (2011).

### 3.2. Linear damping rates

Another uncertainty in determining amplitudes of solar-like pulsations in hotter stars are the modelling of the mode lifetimes (Houdek 2006, Chaplin et al. 2009, Baudin et al. 2011). Although an acceptable agreement between observed heights of solar low-degree modes in the Fourier spectrum and theoretical expectations has been achieved with the help of a time-dependent convection model (Houdek et al. 1999, Houdek & Gough 2002) the largest error in the theory lies in the calculation of the damping rates of low-order modes (Houdek et al. 2001, Chaplin et al. 2005, 2009). We located our principal problem in the stability analyses to be in the convection zone, below the upper boundary layer. An even larger discrepancy between observationally and theoretically inferred acoustic spectral linewidths was reported for solar-like stars that are hotter than the Sun (e.g., Houdek 2006, 2009). For example, with the help of hydrodynamical simulations (Stein et al. 2004), it was found that the theory underestimates the damping rates of the most prominent modes by a factor of two, and possibly more, for the F5 solar-like star Procyon (Houdek 2006). This failure in the theory has recently been confirmed by using average linewidth measurements of solar-like oscillations in several hundreds of stars observed by Kepler (Chaplin 2010, personal communication, see also Appourchaux et al. 2012).

Current theories (Chaplin et al. 2009) predict the average mode linewidth to scale with the fourth power of the stars effective temperature, whereas preliminary Kepler data suggest a steeper dependence, i.e. larger than four (see also Baudin et al. 2011 using CoRoT, and Appourchaux et al. 2012 using Kepler data). As in the case of Procyon, this indicates a failure of our current theory to predict mode linewidths in stars hotter than the Sun, most likely because of a physical mechanism still missing in our current theory. One such crucial mechanism is incoherent scattering at the inhomogeneous upper boundary layer (Murray 1993; Goldreich & Murray 1994), which becomes increasingly more important for stars with higher masses and effective temperatures.

Murray (1993) and Goldreich & Murray (1994) were one of the first to have stressed the importance of the contribution of incoherent scattering ( $\eta_{\text{scatt}}$ ) to the mode

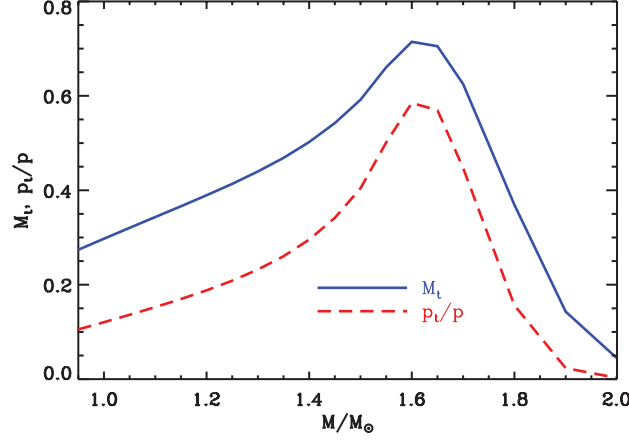


Figure 6. Maximum values of the turbulent Mach number  $M_t := w/c$  and turbulent pressure  $p_t := \langle \rho w w \rangle$  (angular brackets denote an ensemble average) versus stellar mass for models along the ZAMS (adapted from Houdek & Gough 1998).

linewidths, and that it may dominate over other agents contributing to mode damping. They derived in the geometrical optics limit, at the top of the convective envelope, the scattering contribution

$$\eta_{\text{scatt}} \sim \frac{\omega_r M_t^2}{\pi(n+1)} \quad (8)$$

for a radial mode with order  $n$  and frequency  $\omega_r$ , which is proportional to the squared turbulent Mach number  $M_t$ .

It was recognised by Houdek & Gough (1998) that the turbulent Mach number increases rapidly with stellar mass and surface temperature (see Figure 6). Consequently the scattering contribution to the mode linewidths may therefore dominate over the other contributions for stars with high surface temperatures, or more precisely, for stars with turbulent Mach numbers considerably larger than in the Sun. Hot stars have relatively shallow surface convection zones but very vigorous turbulent velocity fields (e.g. Houdek & Gough 1998).

Goldreich & Murray (1994) adopted in their scattering model a time-independent, mixing-length-like, convection model and concluded that the mode energy is most effectively scattered into other modes of similar frequency but higher spherical degree, with the surface gravity mode (f mode) being the ultimate recipient of the scattered energy. A time-dependent treatment of the turbulent velocity field will increase the frequency range of the modes over which the pulsation energy can be scattered (Gough 1977a). An immediate question to be asked here is what the frequency distribution of this process will be, because the distribution determines not only the mode linewidths but also the shape of the spectral peaks in the oscillation power spectrum (e.g., Rast & Gough 1995; Rast 1999). Moreover, if the frequency behaviour of the damping process is similar to that of the stochastic excitation process, which is very likely the case (e.g. Houdek et al. 1999), we would be in the position to put further constraints on the frequency factor of the turbulent velocity spectrum in any stochastic excitation model (e.g. Houdek 2010).

**Acknowledgments.** I am thankful to Reza Samadi for providing some of the numbers listed in Table 1 and to the KITP staff of UCSB for their warm hospitality during the research programme “Astero-seismology in the Space Age”. This work was supported by the Austrian Science Fund (FWF), Project P21205-N16, and in part by the National Science Foundation of the United States under Grant No. NSF PHY05–55164.

## References

- Appourchaux T., Belkacem K., Broomhall A.-M., Chaplin W.C., Gough D.O., Houdek G., Provost J., et al., 2010, *A&A Rev.*, 18, 197
- Appourchaux T., Chaplin W.J., Benomar O., et al., 2012, submitted to *A&A*
- Arentoft T., Kjeldsen H., Bedding T.R., Bazot M., Christensen-Dalsgaard J., Dall T.H., Karoff C., Carrier F., et al., 2008, *ApJ*, 687, 1180
- Baker N., Gough D.O., 1979, *ApJ*, 234, 232
- Balmforth N.J., 1992, *MNRAS*, 255, 603
- Baudin F., Barban C., Belkacem K., et al., 2011, *A&A*, 529, A84
- Belkacem K., Samadi R., Goupil M.-J., Dupret M.-A., Brun A.S., Baudin F., 2009, *A&A* 494, 191
- Belkacem K., Samadi R., Goupil M.-J., et al., 2010, *A&A*, 522, L2
- Breger M., Lenz P., Antoci V., Guggenberger E., Shobbrook R.R., et al., 2005, *A&A*, 435, 955
- Chaplin W.J., Houdek G., Elsworth Y., Gough D.O., Isaac G.R., New R., 2005,
- Chaplin W.J., Houdek G., Karoff C., Elsworth Y., New R., 2009, *A&A*, 500, 21 *MNRAS*, 360, 859
- Chaplin W.J., Kjeldsen H., Christensen-Dalsgaard J., et al., 2011, *Science*, 332, 213
- Dupret M.-A., Grigahcène A., Garrido R., et al., 2005, *A&A*, 435, 927
- Garca R.A., Hekker S., Stello D., Gutierrez-Soto J., Handberg R., et al., 2011, *MNRAS*, 416, 6
- Gabriel M., 1987, *A&A*, 175, 125
- Gabriel M., 1996, *Bul. Astron. Soc. India*, 24, 233
- Goldreich P., Keeley D.A., 1977, *ApJ*, 211, 934
- Goldreich P., Murray N., 1994, *ApJ*, 424, 480
- Gough D.O., 1965, in *Geophys. Fluid Dynamics*, Woods Hole Oceanographic Institutions, Vol. 2, Woods Hole, Mass., p. 49
- Gough D.O., 1969, *J. Atmos. Sci.*, 26, 448
- Gough D.O., 1977a, *ApJ*, 214, 196
- Gough D.O., 1977b, in *Problems of stellar convection*, ed. E. Spiegel, J.-P. Zahn (Berlin: Springer-Verlag), 15
- Grigahcène A., Dupret M.-A., Gabriel M., et al., 2005, *A&A*, 434, 1055
- Guenther D.B., Kallinger T., Gruberbauer M., Huber D., et al., 2008, *ApJ*, 687, 1448
- Houdek G., 2000, in *Delta Scuti and Related Stars*, Breger M., Montgomery M.H., eds, ASP Conf. Ser., Vol. 210, Astron. Soc. Pac., San Francisco, p. 454
- Houdek G., 2006, in *SOHO18/ GONG 2006/ HelAs I: Beyond the spherical Sun*, Fletcher K., Thompson M.J., eds, ESA SP-624, Noordwijk, p. 28.1
- Houdek G., 2008, *CoAst*, 157, 137
- Houdek G., 2009, in *Stellar pulsation: Challenges for Theory and Observations*, Guzik, J., Bradley P., eds, AIP Conf. Proc., Vol. 1170, AIP, New York, p. 519
- Houdek G., 2010, *Ap&SS*, 328, 972

- Houdek G., 2011, in PLATO Science meeting (Februar 2011), Technische Universität Berlin.  
([http://www-astro.physik.tu-berlin.de/plato-2011/talks/PLATO\\_SC2011\\_S07T04\\_Houdek.pdf](http://www-astro.physik.tu-berlin.de/plato-2011/talks/PLATO_SC2011_S07T04_Houdek.pdf))
- Houdek G., Gough D.O., 1998, in SOHO 6/GONG 98: Structure and dynamics of the interior of the Sun and Sun-like stars, Korzennik S.G., Wilson A., eds, ESA SP-418, Noordwijk, p. 47
- Houdek G., Gough D.O., 2002, MNRAS, 336, L65
- Houdek G., Balmforth N., Christensen-Dalsgaard J., 1995, in Proc. 4th SOHO Workshop, J.T. Hoeksema, V. Domingo, B. Fleck, B. Battrick, eds, ESA SP-376, Vol. 2, Noordwijk, p. 447
- Houdek G., Balmforth N.J., Christensen-Dalsgaard J., Gough D.O., A&A, 1999, 351, 582
- Huber D., Bedding T.R., Stello D., Hekker S., Mathur S., et al., 2011a, ApJ, in the press, (arXiv:1109.3460)
- Huber D., Bedding T.R., Arentoft T., Gruberbauer M., Guenther D.B., Houdek G., et al., 2011b, ApJ, 731, 94
- Jiménez A., Roca Cortés T., Severino G., Marmolino C., 1999, ApJ, 525, 1042
- Jiménez A., 2002, ApJ, 581, 736
- Kaneda, Y., 1993, Phys. Fluids A, 5, 2835
- Kolmogorov A.N., 1941, Dokl. Akad. Nauk SSSR, 30, 299
- Lighthill M.J., 1952, Proc. Roy. Soc., A 211, 564
- Martic M., Schmitt J., Lebrun J.-C., Barban C., Connes P., Bouchy F., Michel E., Baglin A., Appourchaux T., Bertaux J.-L. 1999, A&A 351, 993
- Murray N., 1993, in Seismic investigations of the Sun and Stars, Brown T.M., ed., ASP Conf. Ser., Vol. 42, Astron. Soc. Pac., San Francisco, p. 3.
- Rast M.P., 1999, ApJ, 524, 462
- Rast M.P., Gough D.O., 1995, in Proc. GONG '94: Helio- and Asteroseismology from the Earth and Space, Ulrich R.K., Rhodes Jr E.J., Däppen W., eds, ASP Conf. Ser., Vol. 76, Astron. Soc. Pac., San Francisco, p. 332
- Samadi R., Goupil M.-J., 2001, A&A, 370, 136
- Samadi R., Nordlund Å., Stein R.F., Goupil M.-J., Roxburgh I. 2003, A&A, 404, 1129
- Schrijver C.J., Jiménez A., Däppen W., 1991, A&A, 251, 655
- Spiegel E.A., Veronis G., 1960, ApJ, 131, 442 (correction: ApJ, 135, 665)
- Stein R.F., 1967, Solar Phys., 2, 385
- Stein R.F., 1968, ApJ, 154, 297
- Stein R.F., Georgobani D., Trampedach R., Ludwig H.-G., Nordlund Å., 2004, Solar Phys., 220, 229
- Tennekes H., Lumley J.L. 1972, A First Course in Turbulence, The MIT Press
- Unno W., 1967, PASJ, 19, 40
- Unno W., 1977, in Problems of Stellar Convection, Spiegel E.A., Zahn J.-P., eds, Springer-Verlag, Berlin, p. 315
- Unno W., Osaki Y., Ando H., Saio H, Shibahashi H., 1989, Nonradial Oscillations of Stars, Second Edition, University of Tokyo Press
- Vernazza J.E., Avrett E.H., Loeser R. 1981, ApJS, 45, 635
- Xiong D.R., 1977, Acta Astron. Sinica, 18, 86
- Xiong D.R., 1989, A&A, 209, 126
- Xiong D.R., Cheng Q.L., Deng L., 2000, MNRAS, 319, 1079
- Xiong D.R., Deng L., 2001, MNRAS, 324, 243
- Xiong D.R., Deng L., 2007, MNRAS, 378, 1270